Spatial Filter Technology Development

Christian d'Aubigny, Christopher Walker,
Dathon Golish, Udo Wehmeier

Steward Observatory
University of Arizona

Ducan Liu

JPL

Presentation Outline

- Introduction
- Device
  - Spatial Filter Operation Principle
  - Horn Design
- Theoretical Performance
  - Modal Rejection
  - Throughput
- Process & Technology
  - Heritage
  - TPF Technology Development Effort Status
- Application to Integrated Optics
- Summary

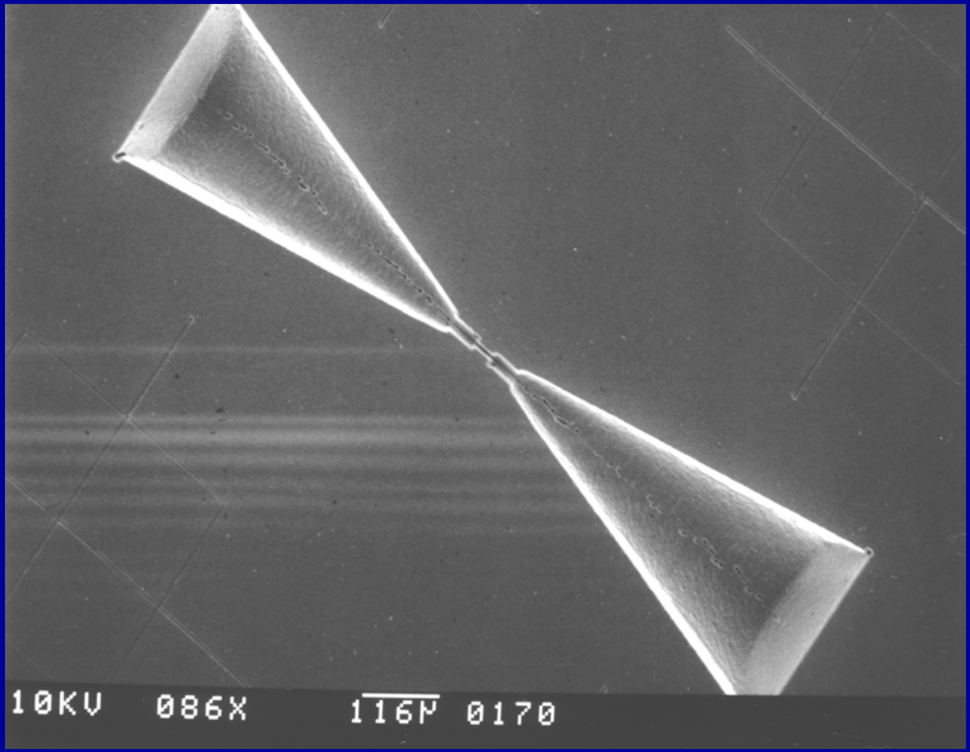
Introduction

In the search for Earth-like extra-solar planets, the high flux ratio between sources requires nulling at the 10^6 level (IR). Small pointing errors, optical aberrations or dust scattering can cause stellar leaks that compromise visibility. Spatial filters have been demonstrated to lower the optical requirements of interferometers and enhance the feasibility of high rejection ratios.

Feedhorns and metallic waveguides are potentially attractive spatial filters:

- Feedhorns couple very efficiently to Gaussian beams (99%)
- Minimal waveguide length needed to attenuate unwanted modes ($\sim\lambda$)
- Low loss, total throughput >75%, no AR coating or complex materials
- Feedhorn geometry allows to trade tilt and shift tolerance
- Devices can be fabricated using laser micromachining technology

Device



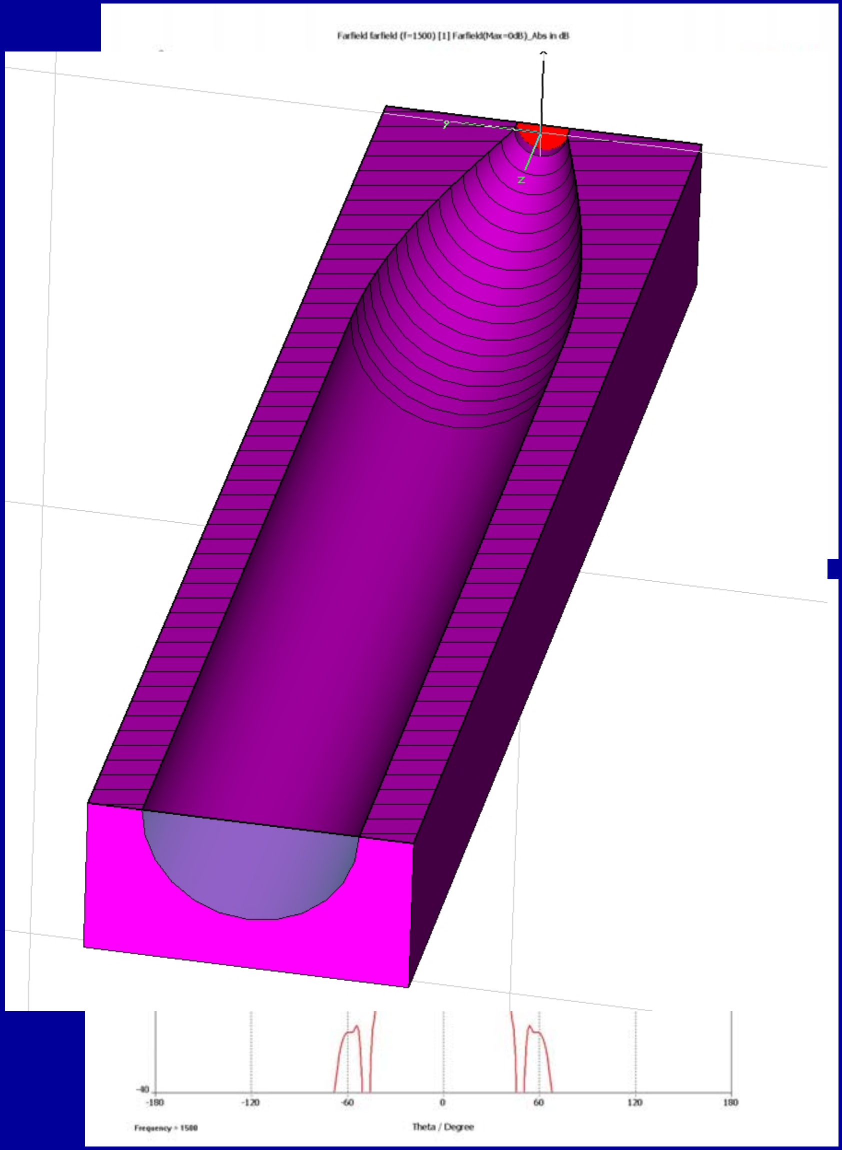
Feedhorns very efficiently couple a Gaussian beam into a single mode waveguide.

1. Field overlap integral of horn radiation pattern and Gaussian >99% (Neilson 2002).

2. At λ=10μm, a 10 μm long, single mode waveguide, provides 60 dB of attenuation between the dominant mode and the second lowest mode

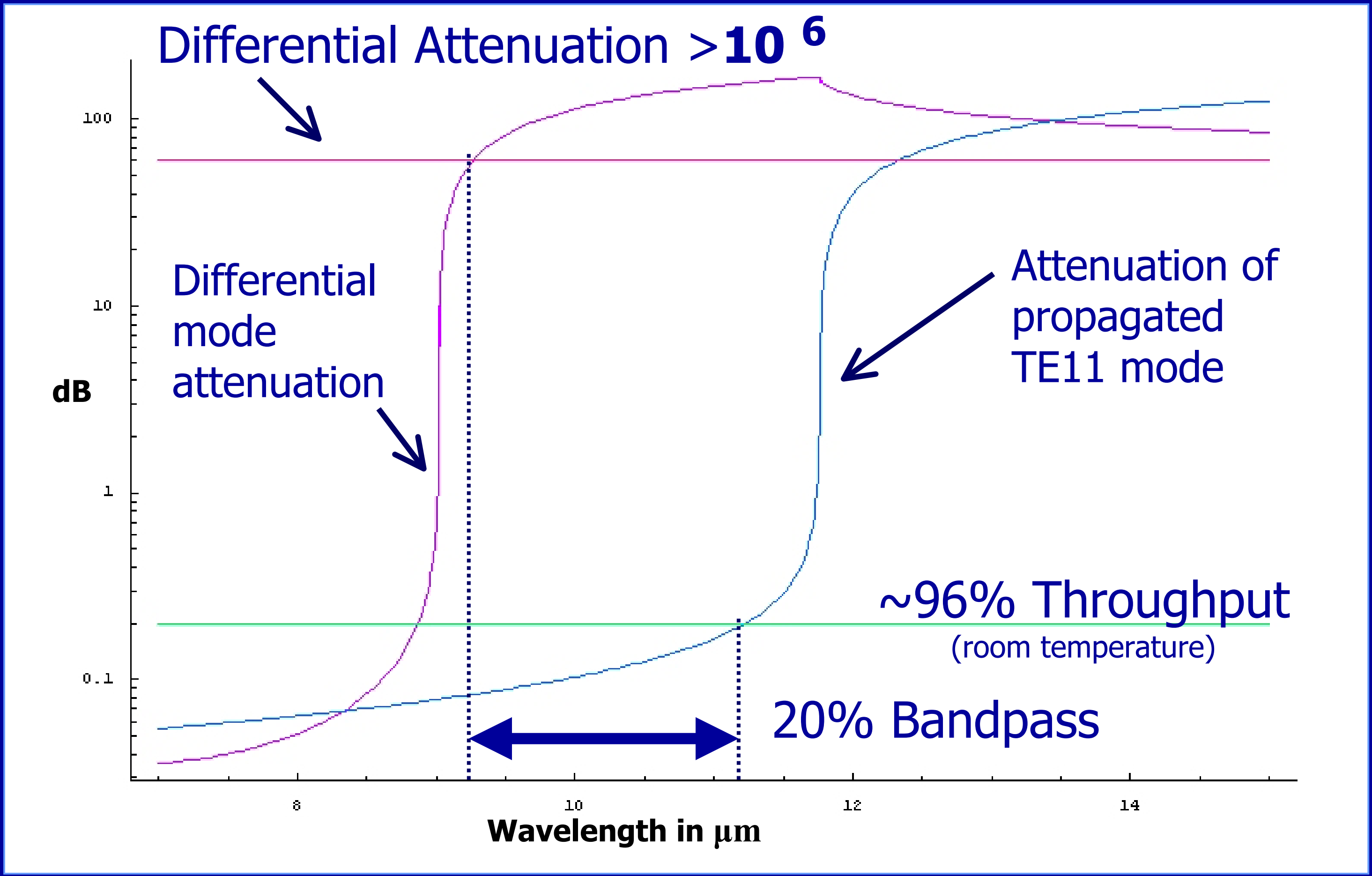
Nielson* Horn Design and Performance

- Smooth walls easy to machine
- Circularly Symmetric Device → Polarization Insensitive
- Gaussian Beam Coupling Efficiency: 99%
- Very Low Side Lobes (-30 dB)
- Symmetric Beam Pattern to -25 dB
- Achromatic Injection
- 20% Bandwidth (95% coupling)
- Very Mature Finite Element Modeling Technology.



*J. M. Nielson, "An Improved Multimode Horn for Gaussian Mode Generation at Millimeter and Submillimeter Wavelengths", IEEE Transactions on Antennas and Propagation, Vol 50, No. 8, Aug. 2002

Single Mode Waveguide Bandpass, Throughput and Differential Attenuation



Differential attenuation of TE_{11} and TM_{01} modes in a 10 μm long circular waveguide (purple curve) attenuation of TE_{11} mode (blue curve). Differential attenuation greater than 10^6 is achieved over a 20% bandpass with 96% throughput.

Propagated Mode Attenuation in Metallic Waveguides

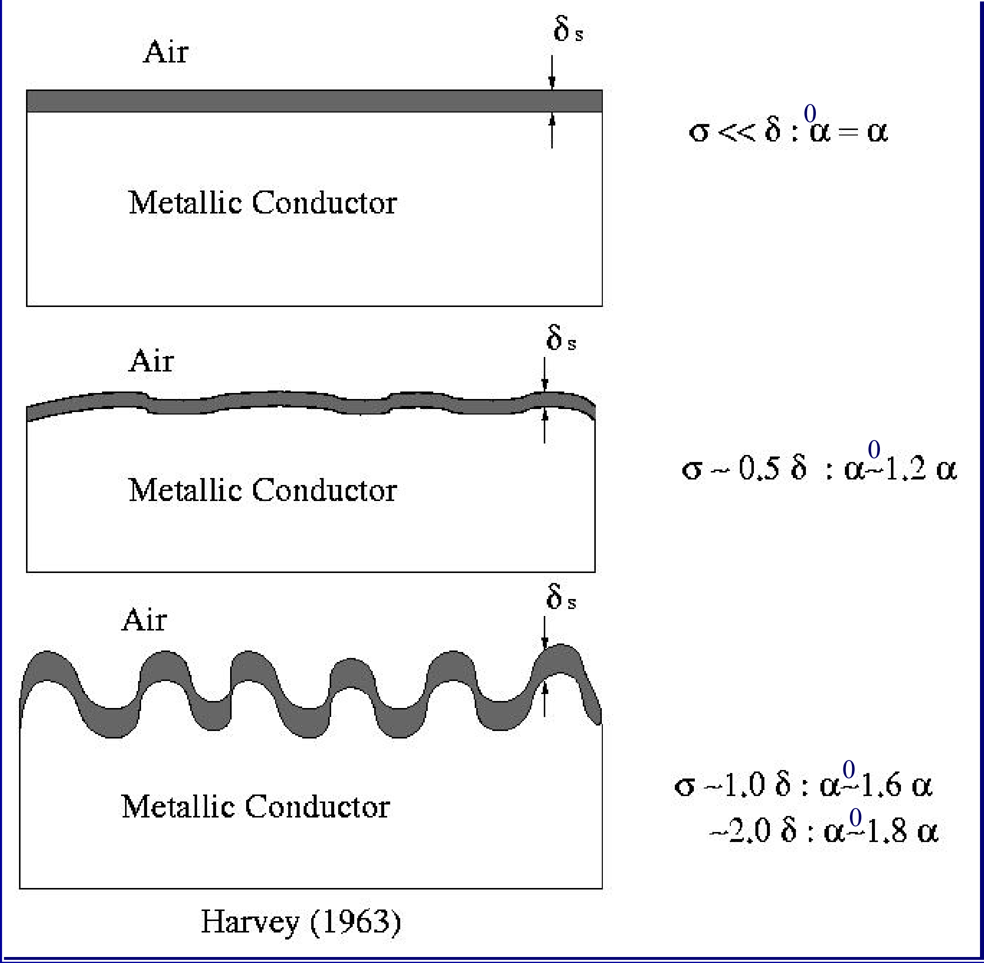
Basic Causes

1. Metals have finite conductivity
2. Surface roughness increases effective current path length

Mitigating Factors

1. Conductivity improves at low temperature
2. Losses can be reduced by aligning the etch (roughness) direction and propagation direction

Surface Roughness Induced Attenuation



Skin depth in gold:
δ_s=13 nm at λ =10 μm

Surface roughness:
σ_s~25 nm r.m.s.

And therefore
$\alpha = 1.8\ \alpha_0$

Predicted Throughput:
93% (room temperature & random etch direction)

Spatial Filter Throughput

- Losses (dB) along a 1 wavelength long (required for modal rejection), 25 nm rms surface roughness, waveguide segment at λ=10 μm

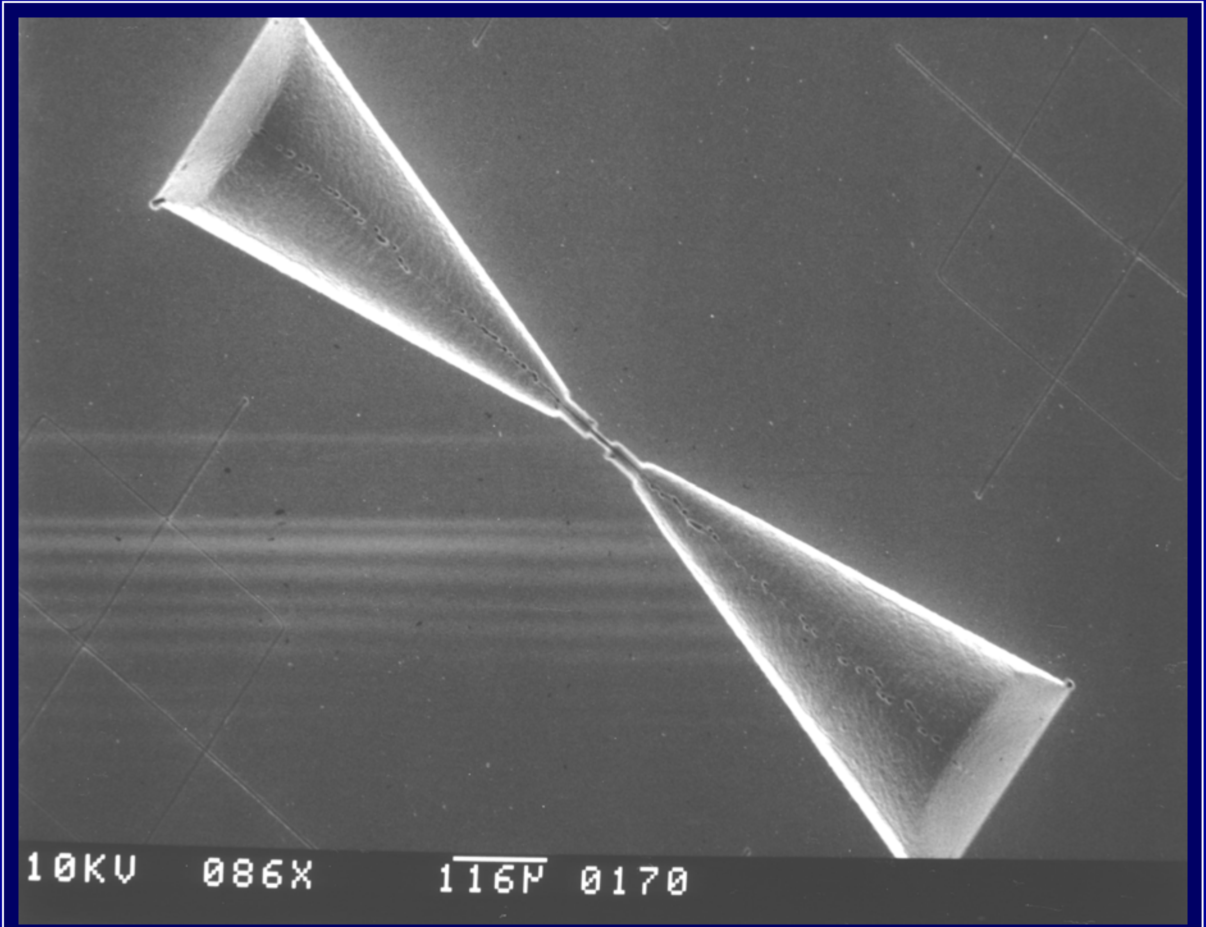
	290 K	90 K	20 K
Random Etch Direction	0.35 dB	0.18 dB	0.12 dB
Etch Along Propagation Direction	0.1 dB	0.054 dB	0.036 dB

- 81%* Coupling efficiency between Gaussian beam and telescope
- 95% Coupling efficiency between horn and Gaussian
- Propagated Mode Attenuation <0.05 dB (>99% Throughput)

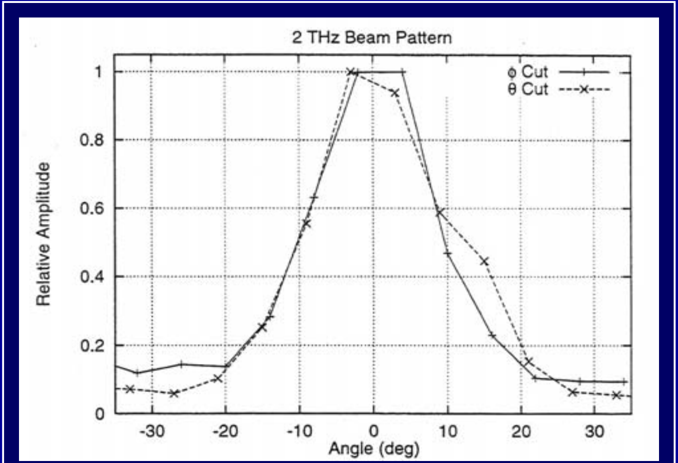
→ Total Device Throughput (6K) > 75%

* C. Ruiller, "A Study of Degraded Light Coupling Into Single-Mode Fibers", SPIE Vol. 3350, p. 319, Kona 1998

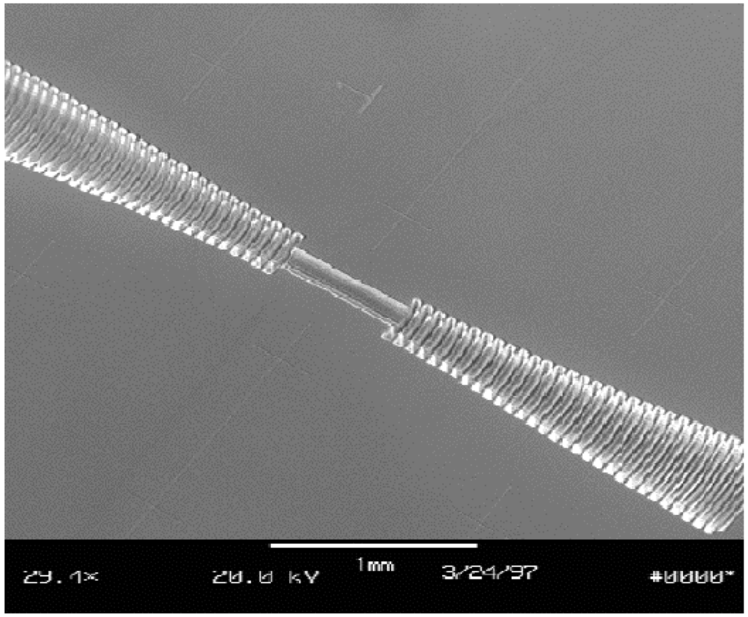
Micromachined Spatial Filters



SEM image of λ =60 µm back to back potter feedhorns for use as a spatial filter



Measured beam pattern of λ = 150 µm back to back feedhorn pictured below



λ = 150 µm back to back feedhorns [UV Epoxy replica]

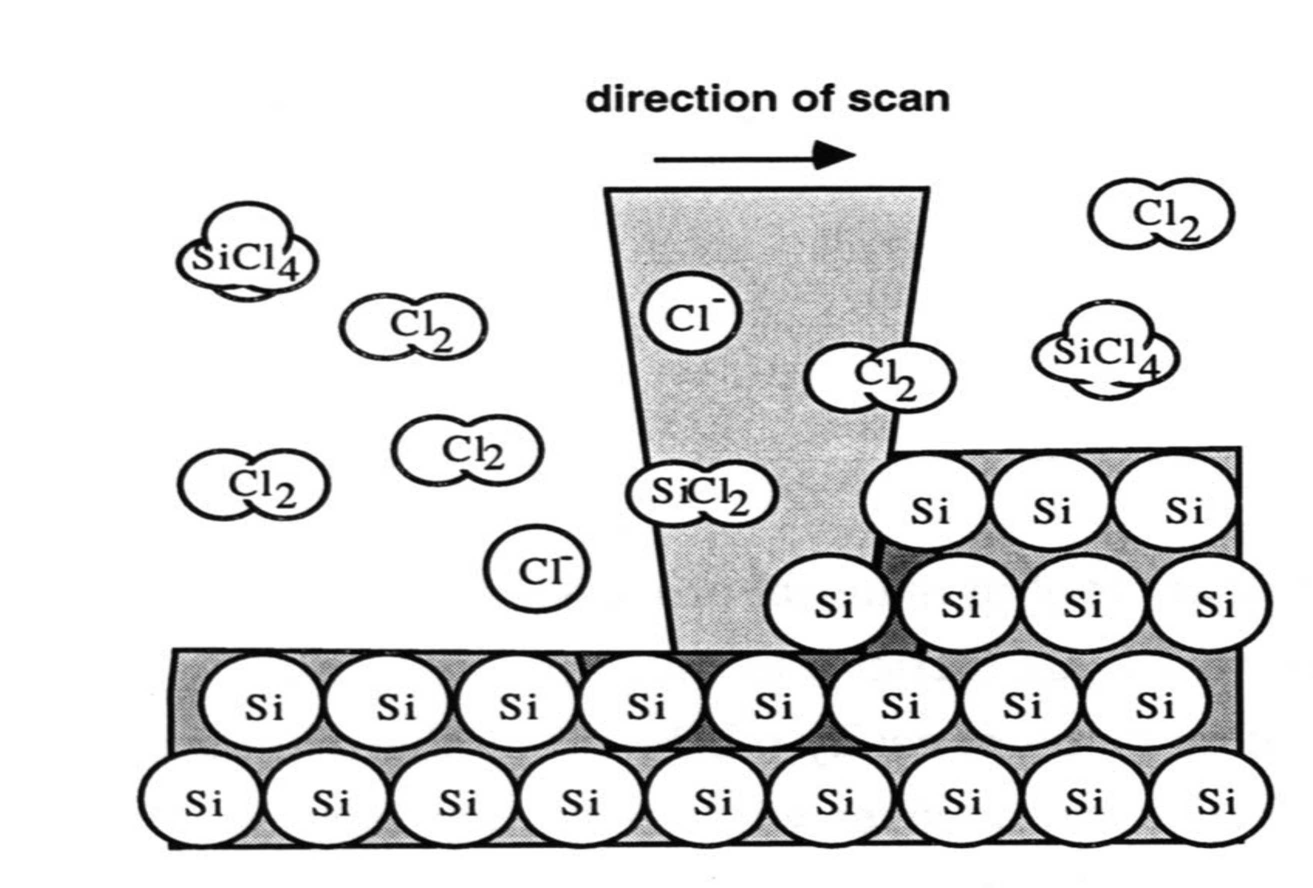
Why Laser Micromachining ?

Laser Micromachining uses a laser-induced micro chemical reaction to etch silicon to μm accuracies.

- No masks required
- Not confined to any crystal planes
- A non-contact process: Eliminates material damage, tool wear and vibration
- Chemical reaction prevents debris
- Etch depth ~5mm
- Allows scaling complex waveguide structures from GHz to THz and mid IR

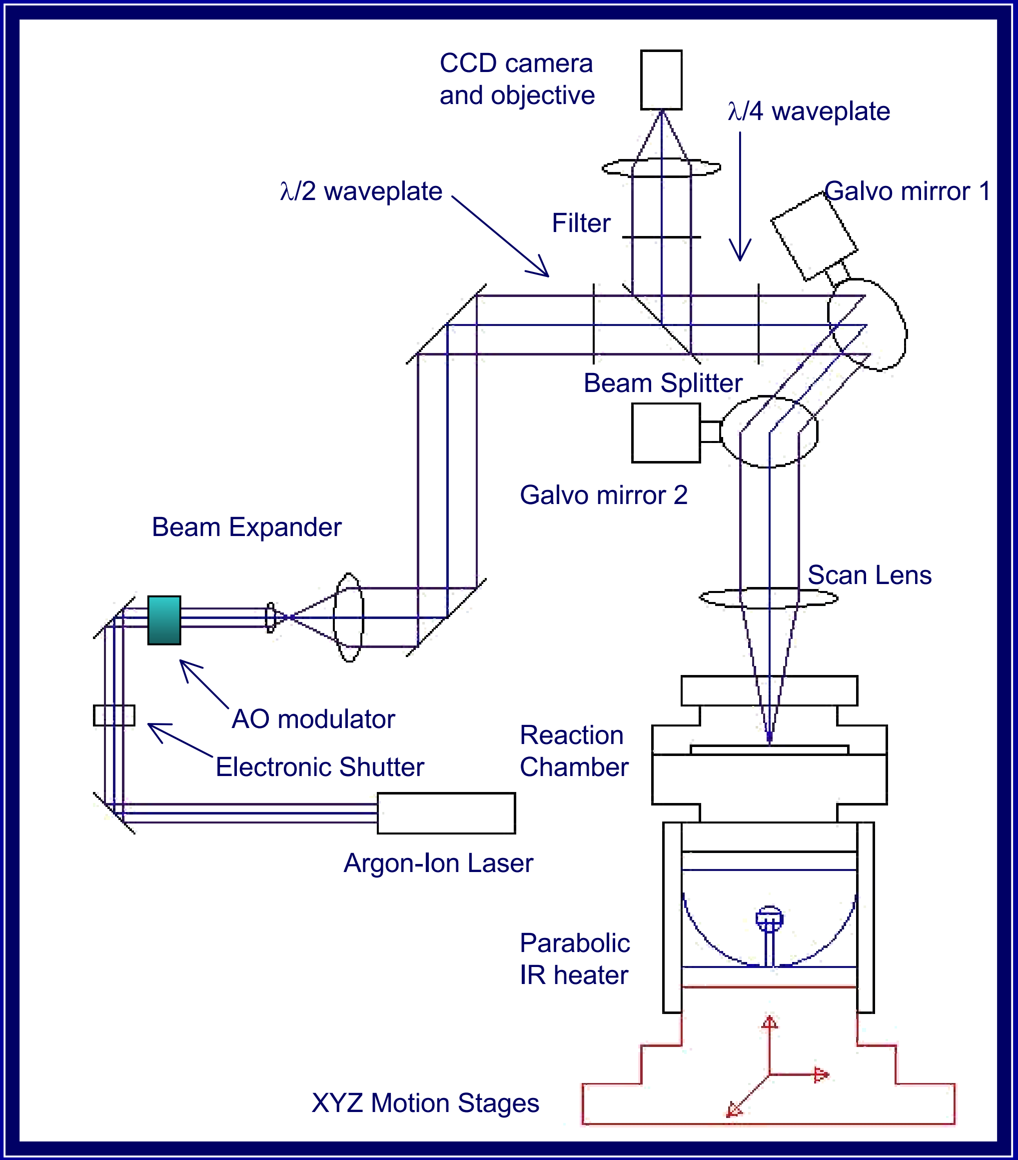
Laser Micromachining Process

- Focus ~4W of laser power on few microns diameter spot
- Silicon evaporates and reacts with chlorine gas
- Silicon that does not react with chlorine re-deposits epitaxially
- Laser spot is scanned at several cm/s removing a 1 micron deep layer at a time
- 3-D Structure is created plane by plane

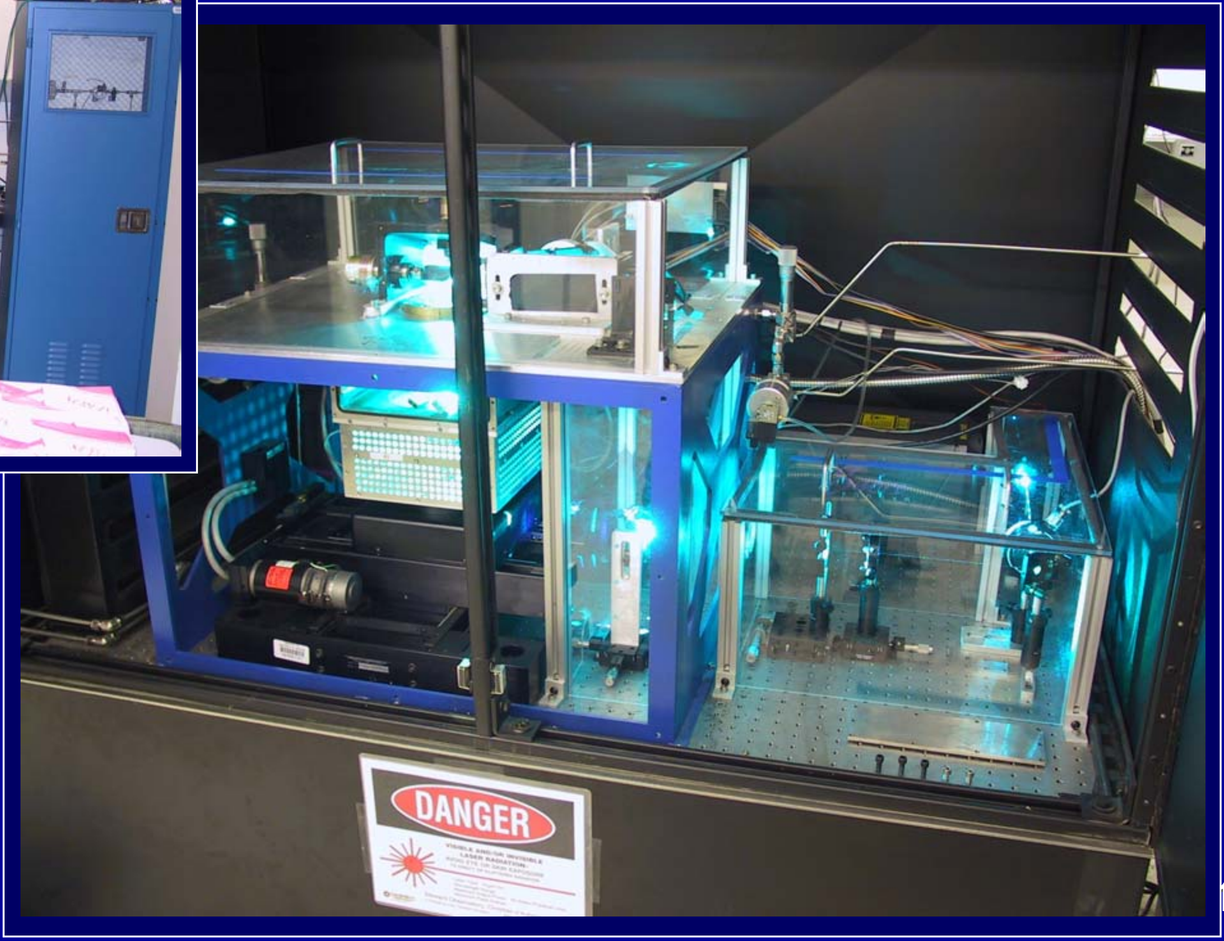


Bloomstein 1996

Schematic of Laser Micromachining System

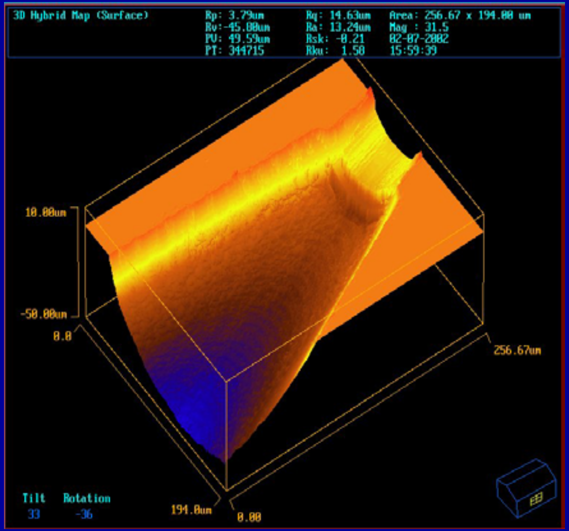


Existing Laser Micromachining System



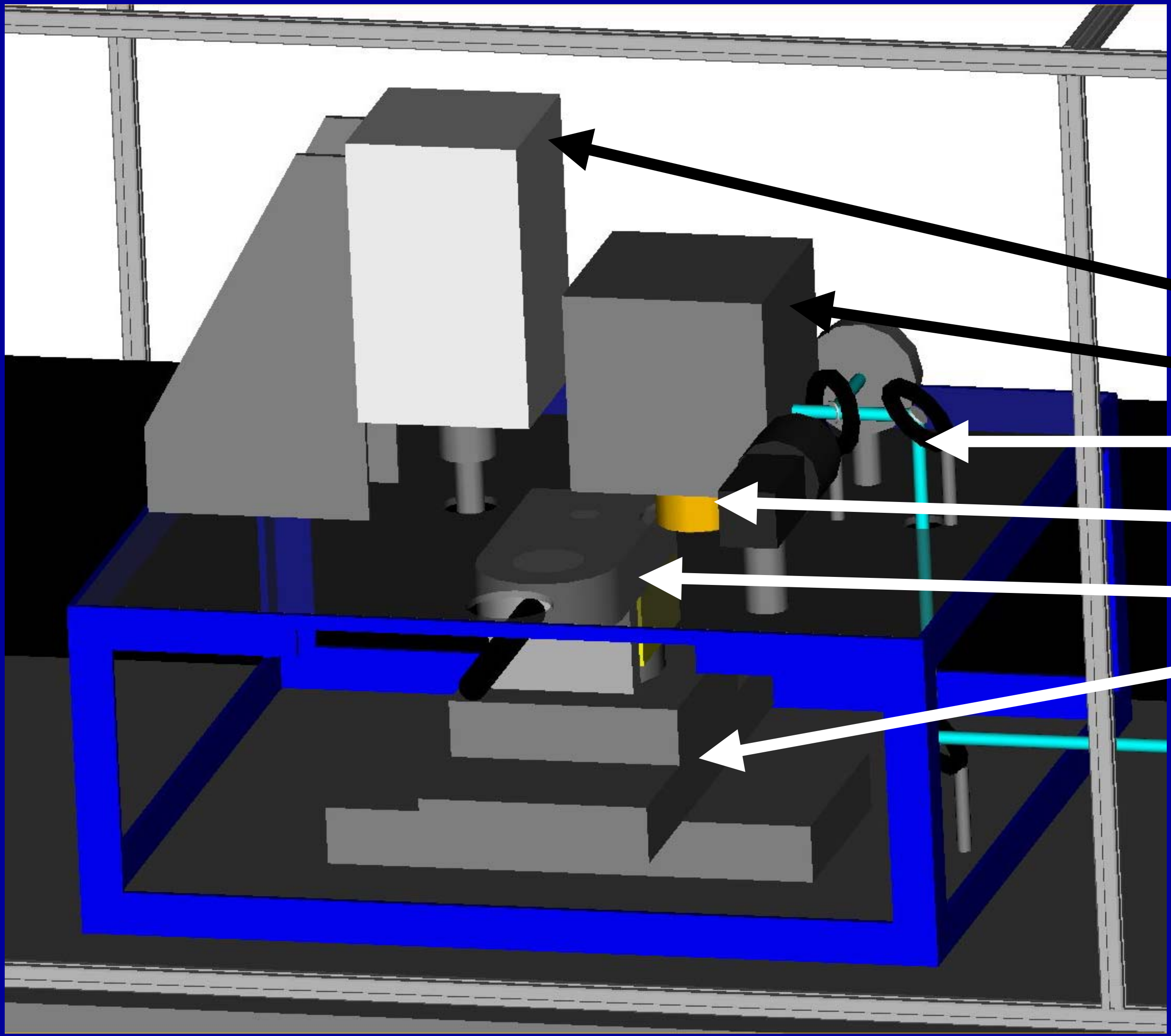
New Laser Micromachining System

The Steward Observatory system was originally designed for the fabrication of devices operating at $\lambda=200\mu m$. Structures for $\lambda=60\mu m$ have been fabricated. To allow the fabrication of devices at the wavelength of interest a next generation laser micromachining system is being assembled at Steward Observatory.



Interferometric Microscope
Image of $\lambda=60$ μm Feedhorn

- Faster optics NA=0.5
- UV laser $\lambda=351nm$
- In-situ Interferometric Metrology
- Load-locked Reaction chamber



New System:

- White Light Metrology
- Improved Galvo System
- UV Laser
- High NA Scan Lens
- Load-locked chamber
- Precision XYZ Stages

Spatial Filter Project Schedule/Status

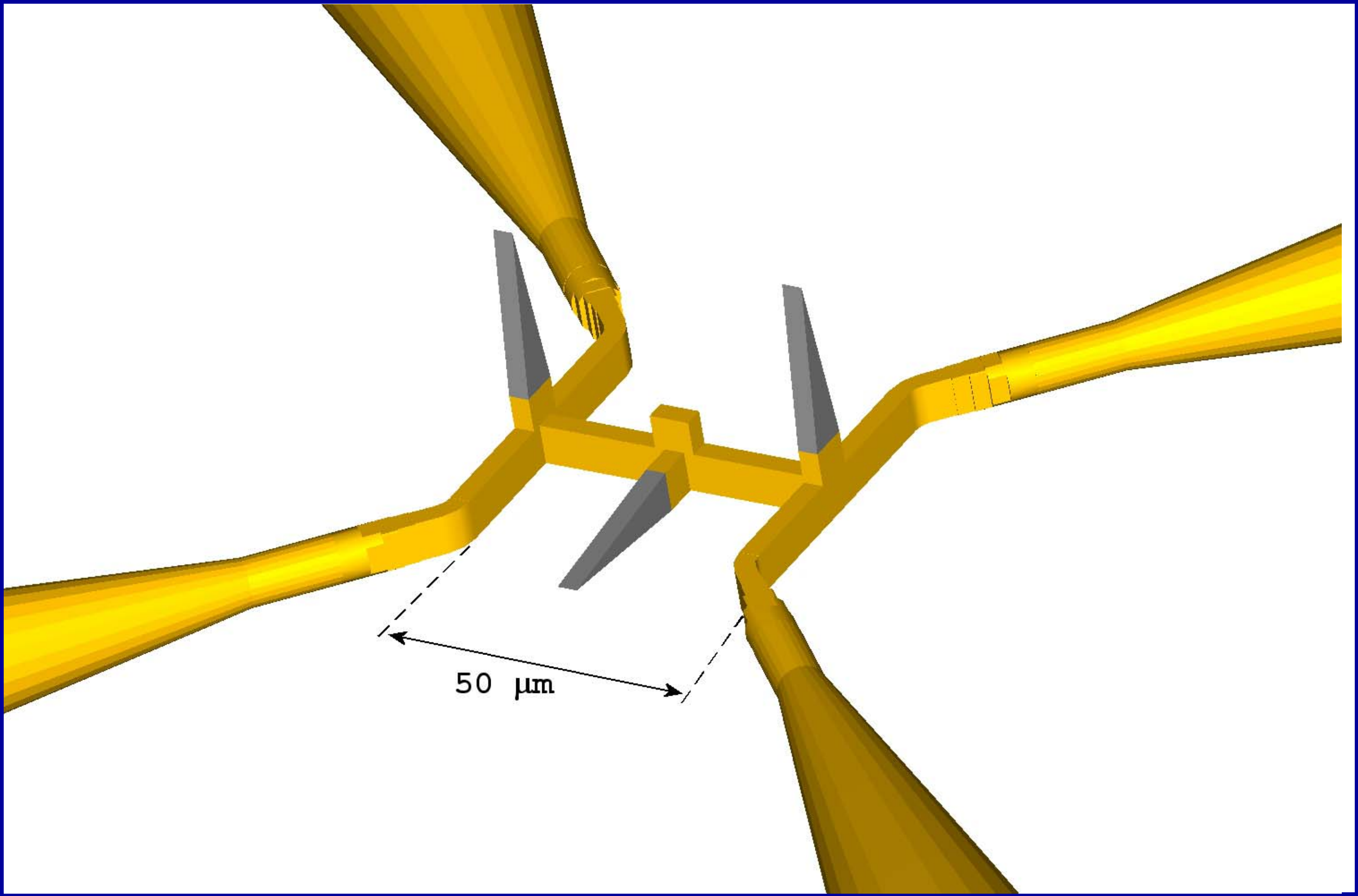
Project Start 7/03

- √ Laser System Design
- √ Improved Horn Design and Modeling
- √ Parts Order

→ Laser System Assembly

- Laser System Operational (winter)
- Filter Fab and Test (Spring 04)
- Prototype Mid IR Spatial Filter delivery (6/04)

IO Double Bracewell Nulling Interferometer Concept



Stable monolithic cryo platform

Single Mode

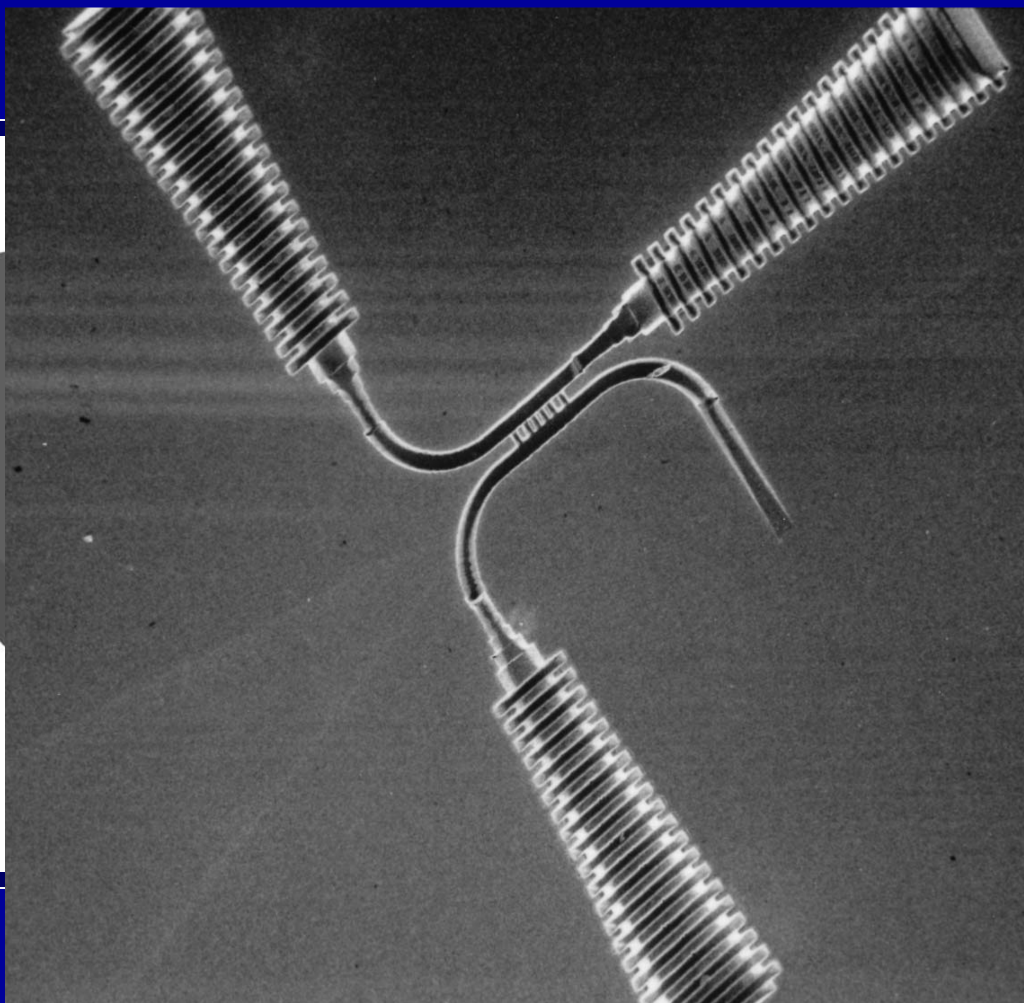
High Throughput (Possibly ~70%)

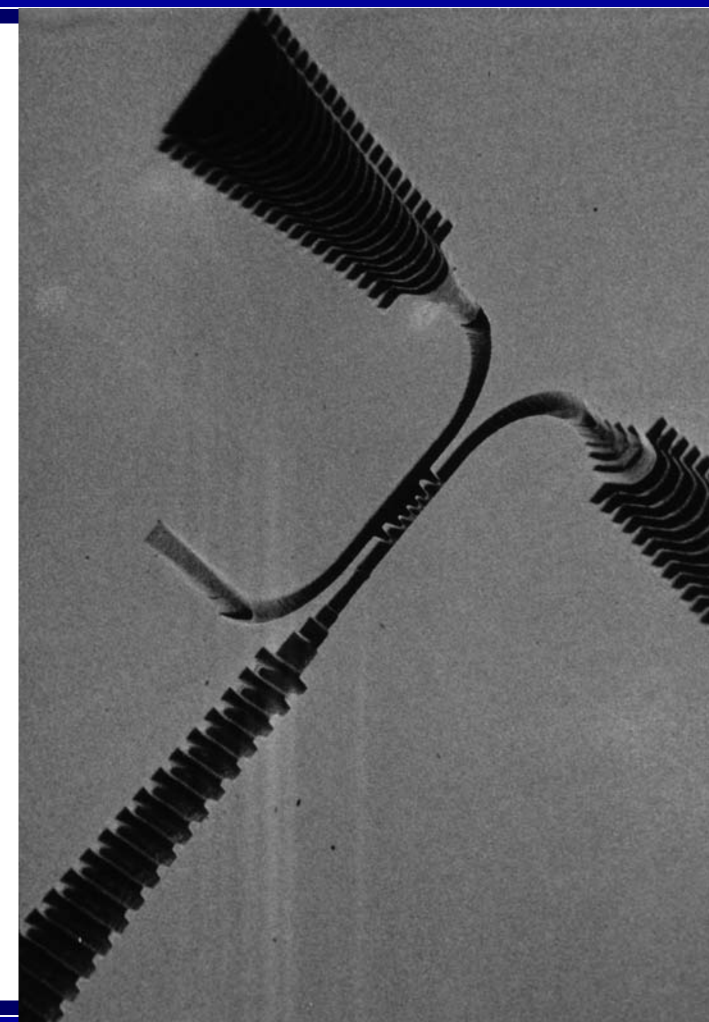
20% Bandwidth can be stacked to cover the whole band

Look for IO posters

- Udo Wehmeier
- Mark Swain

Proof of Concept Integrated Optics Interferometer





Typical IO Nuller Throughput

- Losses (dB) along a 1 wavelength long, 25 nm rms surface roughness, waveguide segment at λ=10 μm

	290 K	90 K	20 K
Random Etch Direction	0.35 dB	0.18 dB	0.12 dB
Etch Along Propagation Direction	0.1 dB	0.054 dB	0.036 dB

- Length of Triple Tee IO Nuller Presented: <12 λ
- Predicted Throughput of the IO Nuller (Etched Along Propagation Axis and held at 90K): > 90 %
- Assuming 81%* coupling efficiency between Gaussian beam and telescope

  Total Efficiency ~ 70%

* C. Ruiller, "A Study of Degraded Light Coupling Into Single-Mode Fibers", SPIE Vol. 3350, p. 319, Kona 1998

Summary

- Metallic feedhorn and waveguide structures can be used to make high efficiency spatial filters for nulling interferometry
- Laser micromachining provides a means of scaling successful feedhorn and waveguide spatial filters to THz frequencies and mid IR
- A new laser micromachining system is being assembled at Steward Observatory as part of TPF technology development and slated to become operational this winter
- This technology can also be used to fabricate integrated optical components that may greatly simplify space interferometer designs

Thank You!